

Interface Design for Interoperability for the Land
Information System
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Increasing Interoperability and Performance of
Grand Challenge
Applications in the Earth, Space, Life, and
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1 Introduction

This document describes the design policy for interoperability for the Land Information System (LIS) [5] implemented under funding from NASA’s ESTO Computational Technologies Project. This design is submitted to satisfy the Task Agreement GSFC-CT-2 under Cooperative Agreement Notice CAN-00-OES-01 increasing interoperability and performance of grand challenge applications in the earth, space, life, and microgravity sciences.

Code interoperability is important not only between components of a research application, but also between different applications, to decrease the cost of development. Research applications with reusable components facilitate faster development of future applications and enables a broader user base.

This document outlines two different types of interoperability that LIS intends to define and adopt:

- **Internal Interoperability:** This is interoperability that is provided by LIS to the land surface modeling community. LIS will provide an interoperable framework for the land surface modeling community by defining adaptive, extensible interfaces for incorporating new land surface models into LIS.
- **External Interoperability:** Participate with Earth, space, life, and microgravity scientific communities by adopting the utilities and compliance guidelines provided by the earth system modeling framework (ESMF) [3]. LIS will also comply with established land surface modeling standards such as assistance for land modeling activities (ALMA) [1].

2 Land Surface Modeling in LIS

In general, land surface modeling seeks to predict the terrestrial water, energy, and biogeochemical processes by solving the governing equations of soil-vegetation-snowpack medium. Land surface modeling combined with data assimilation seeks to synthesize data and land surface models to improve our ability to predict and understand these processes. The ability to predict terrestrial water, energy, and biogeochemical processes is critical for applications in weather and climate prediction, agricultural forecasting, water resources management, hazard mitigation and mobility assessment.

In order to predict water, energy, and biogeochemical processes using (typically 1-D vertical) partial differential equations, land surface models require three types of inputs: (1) initial conditions, which describe the initial state of land surface; (2) boundary conditions, which describe both the upper (atmospheric) fluxes or states, also known as “forcings” and also the lower(soil) fluxes or states; and (3) parameters,

which are a function of soil, vegetation, topography, etc., and are used to solve the governing equations.

LIS uses the LDAS [4] model control and input/output system that drives multiple offline one dimensional land surface models (LSMs) to facilitate global land surface modeling within a data assimilation system framework. LIS is expected to include three different land surface models, namely, CLM [2], NOAH [6], and VIC [7]. The driver in LIS uses various satellite and ground based observation systems within a land data assimilation framework to produce optimal output fields of land surface states and fluxes. In addition to being forced with real time output from numerical prediction models and satellite radar precipitation measurements, LDAS derives model parameters from existing topography, vegetation and soil coverages. The model results are aggregated to various temporal and spatial scales, e.g., 3 hourly, $0.25^\circ \times 0.25^\circ$.

The execution of LIS starts with reading in the user specifications. The user selects the model domain and spatial resolution, the duration and timestep of the run, the land surface model, the type of forcing from a list of model and observation-based data sources, the number of “tiles” per grid square, the soil parameterization scheme, reading and writing of restart files, output specifications, and the functioning of several other enhancements including elevation correction and data assimilation. The LSMs in LIS are driven by atmospheric forcing data such as precipitation, radiation, wind speed, humidity, etc., from various sources. LIS applies spatial interpolation to convert forcing data to the appropriate resolution required by the model. Since the forcing data is read in at regular intervals, LIS also temporally interpolates time average or instantaneous data to that needed by the model at the current time step. Figure 1 shows the modeling structure of LIS.

3 Internal Interoperability in LIS

The concept of “internal” interoperability is to provide an interoperable framework for the land surface modeling community by defining adaptive, extensible interfaces for incorporating new land surface models and other features into LIS. This is the interoperability that is provided by LIS to the land surface modeling community to facilitate adoption of new or improved land surface models and input data.

This is achieved by reorganizing the central driver of LIS. The LIS driver is designed using advanced features of Fortran 90 programming language, which are especially useful for object oriented programming. The LIS driver is designed using object oriented design principles, providing a number of well-defined interfaces or “hook points” for enabling rapid prototyping and development of new features and applications into LIS.

Figure 2 shows the organization of some of the main modules and the main

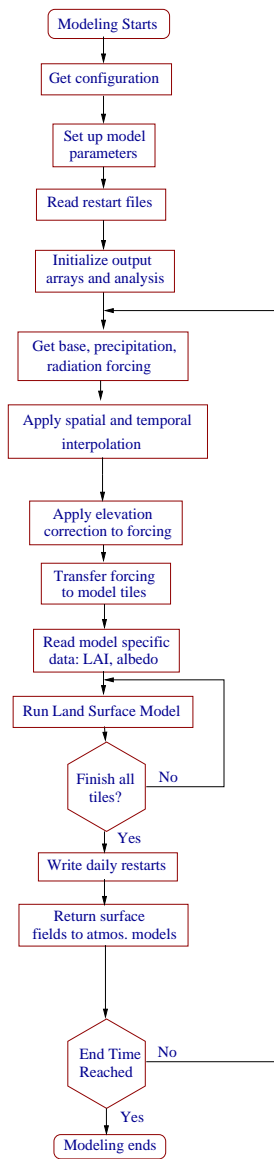


Figure 1: Structure of LIS

driver in LIS. Figure 1 shows the main modeling functions of the driver. The design shown in 2 separates these functions into different modules that capture a certain program behavior. The `ldasdrv_module` contains some of the driver routines, `lsm_module` captures the main functionalities associated with the operation of a land surface model, `baseforcing_module` provides abstractions of model forcing behavior, `obsradforcing_module` and `obsprecipforcing_module` captures the observed

radiation and observed precipitation forcing behavior, respectively, and `spmdMod` and `lislog_module` provides routines for parallel environment control and error/log diagnostic control, respectively. Each of these modules contain extensible interfaces for the program segment it represents. For example, `lsm_module` provides interfaces and subroutines required for initialization, execution, restart and managing output of an LSM. A more detailed organization is shown in Figure 3.

The main driver that initializes other modules is represented by `lisdrv`. `lisdrv` initializes parallelization routines through `spmdMod` and the driver routines through `ldasdrv_module`. `ldas_module` contains the variables for LSM initializations, executions and outputs. The representation and management of time is encompassed in `time_module` and `grid_module` contains the variables used for spatial grid representation. `baseforcing_module` includes interfaces that are used to incorporate different atmospheric and observation forcings. As explained earlier, `lsm_module` provides interfaces that can be extended to incorporate new LSMs.

The modules in LIS are constructed using a component-based design. As mentioned earlier, each module/component represents a program segment that is functionally related. The interfaces are implemented by using a number of virtual function tables and the actual delegation of the calls are done at runtime by resolving the function names from the table. C language allows the capabilities to store functions, table them and pass them as arguments. F90 allows passing of functions as arguments. By combining both these languages, LIS uses a complete set of operations with function pointers.

Figure 4 shows the interfaces in the `lsm_module`. To incorporate a new LSM in LIS, methods corresponding to each of these interfaces need to be implemented. Once these methods are implemented, they need to be stored in the virtual function tables that correspond to these interfaces. The register functions shown in Figure 5 enable the creation of virtual function tables.

Similar constructs using virtual function tables are employed for other modules such as `baseforcing_module`, `obsradforcing_module`, and `obsprecipforcing_module`, enabling the definition of explicit interfaces that are functionally relevant only to the respective program segment.

The design of LIS driver presented above achieves encapsulation of data and control. The underlying representation does not need to be changed to incorporate a new forcing or a new LSM. The code also simulates polymorphism by allowing the initializations and executions to be determined at runtime. For example, `lsm_module` contains a global table of pointers for each LSM in the inheritance hierarchy. `lsm_module` acts as a polymorphic class, delegating the program flow based on the global pointer that is instantiated. This method also helps in facilitating defining operation of ensembles of LSMs in addition to individual LSMs. Together, these concepts help to organize the code, making them more flexible, maintainable, and extensible.

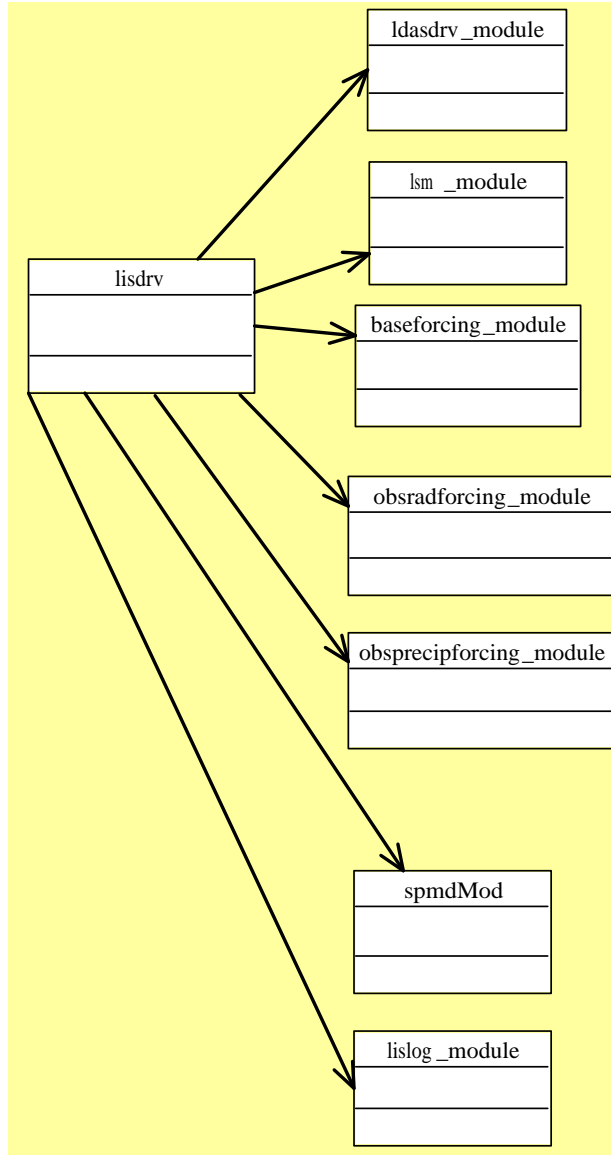


Figure 2: Organization of main modules in LIS driver

4 External Code Interoperability in LIS

To demonstrate interoperability with other scientific modeling communities, LIS will comply with the ALMA data exchange convention and employ the utilities and extensible interfaces provided by ESMF.

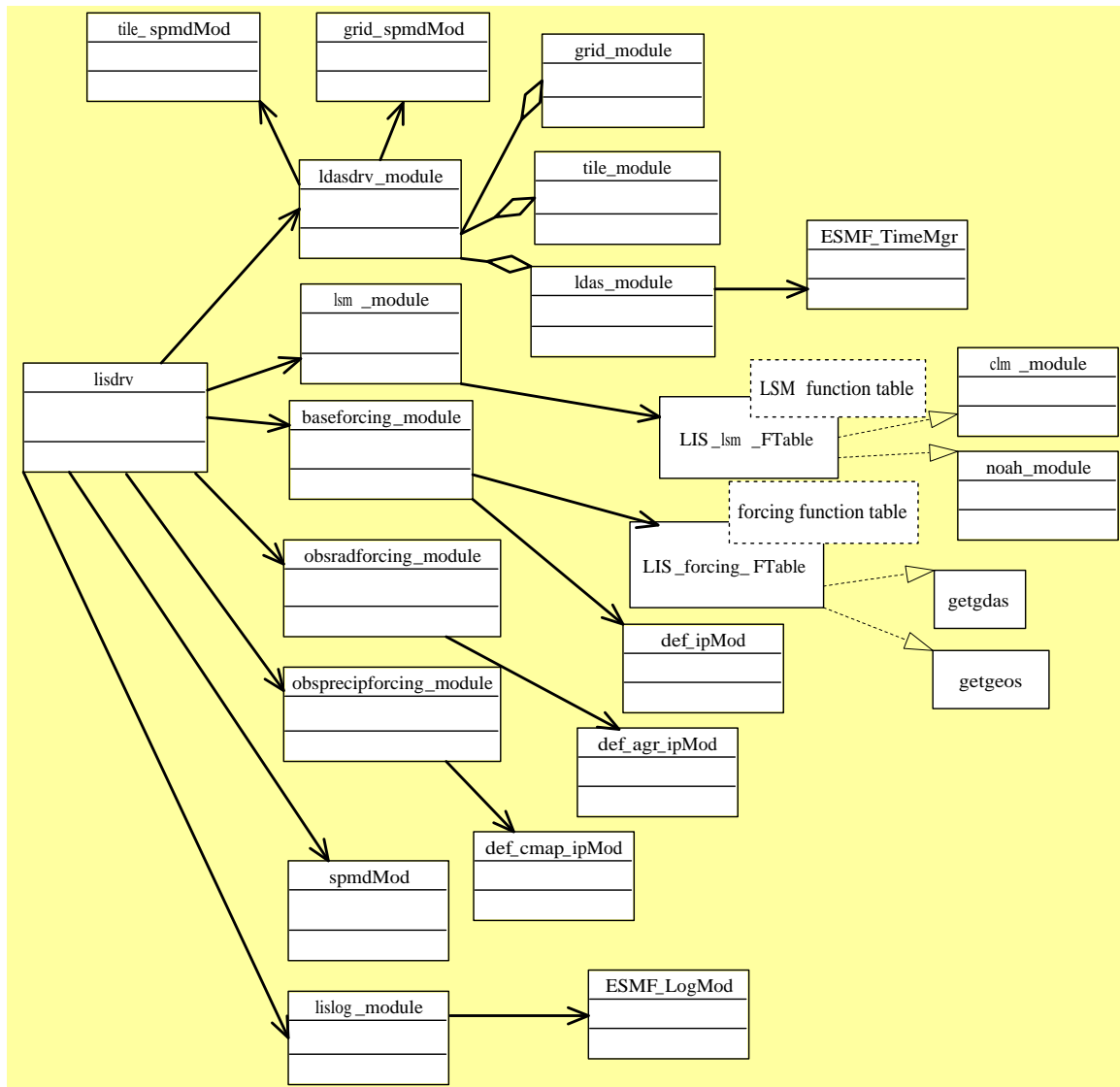


Figure 3: Detailed organization of modules in LIS driver

4.1 LIS and ESMF

The purpose of ESMF is to develop a framework that provides a structured collection of building blocks that can be customized to develop model components. ESMF can be broadly viewed as consisting of an infrastructure of utilities and data structures for building model components and a superstructure for coupling and running them. The use of ESMF interfaces and utilities in LIS allows for future coupling with earth system models such as atmospheric models.

```

interface LIS_lsm_init      !Methods for initialization
interface LIS_setuplsm      !Methods for LSM setup
                             !(parameter initializations)
interface LIS_setDynlsm     !Methods to set time dependent
                             !parameters
interface LIS_force2tile    !Transfer forcing data to model tiles
interface LIS_lsm_main      !LSM execution for a timestep
interface LIS_readrestart   !Routines to read a restart file
interface LIS_writerestart  !Routines to write a restart file
interface LIS_lsm_output    !Routines to write model output

```

Figure 4: Interfaces in `lsm_module`

```

call registerlsmini(noah_varder_ini)
    ! Registers noah's initialization function
call registerlsmsetup(noah_setup)
    ! Registers noah's setup function
call registersetdynlsm(noah_setdyn)
    ! Registers noah's dynamic setup routines
call registerf2t(noah_f2t)
    ! Registers forcing transfer function for noah
call registerlsmrun(noah_main)
    ! Registers noah's execution routine
call registerlsmoutput(noah_output)
    ! Registers noah's output routine
call registerlsmreadrestart(noahrst)
    ! Registers noah's restart reading routine
call registerlsmwriterestart(noah_writerestart)
    ! Registers noah's restart writing routine

```

Figure 5: Register functions in `lsm_module`

4.2 ESMF Infrastructure Adoption

The ESMF infrastructure layer contains both higher level data handling objects and lower level utility routines. The infrastructure layer provides abstractions for fields and group of fields discretized on grids in classes such as `Field`, `Grid`, `Bundle`

etc. LIS plans to adopt these representations necessary for implementing coupled applications and to make use of some of the infrastructure utilities such as Regrid.

The utility layer presents a uniform interface for common system functions such as time manager, basic communications, error handler, diagnostics, etc. LIS currently uses the ESMF time manager and the logging and error diagnostics tools. The time management utility provides useful functions for time and data calculations and higher level functions that control model time stepping and alarms. The log utility organizes diagnostic output and allows for searches and filters to be constructed. The error handler provides both uniform handling of errors and a way for users to select how the errors will be handled. Figure 6 shows a schematic view of the interaction between LIS and ESMF infrastructure. The solid lines represent the utilities currently used by LIS and the dotted lines represent the some of the tools that will be implemented in the future.

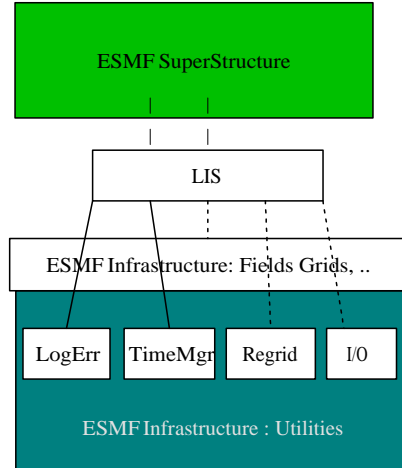


Figure 6: LIS and ESMF

4.3 ESMF Superstructure Adoption

ESMF also defines a number of guidelines for applications that are intended to be coupled with other Earth system models. ESMF provides definitions of a **Gridded Component** class for user-supplied components discretized on grids and a **Coupler Component** class for the software that is used to couple them together. LIS will implement the interfaces required to be a **Gridded Component** and will use **ESMF_State** class to exchange information with other models and systems. A land surface model can be coupled with other earth system models by implementing it as a **Gridded Component**. However, since LIS provides the infrastructure to drive different offline

land surface models, implementing LIS itself as a **Gridded Component** will allow any LSM in LIS to be used for coupling with other earth system models. LIS could serve as the land modeling component in the coupled system, providing the best possible surface fluxes to the atmospheric modeling components. Figure 7 shows a simple sequence diagram for running an application with LIS being coupled to an atmospheric model, exchanging data through custom-defined couplers.

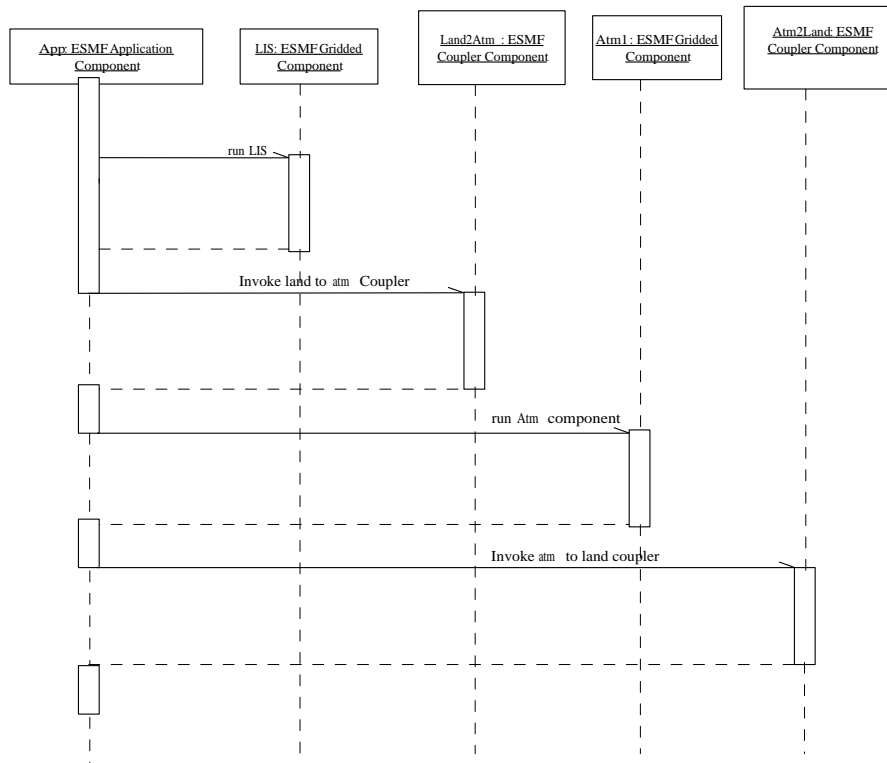


Figure 7: Sequence diagram for running a simple coupled application using LIS as an ESMF Gridded Component

The LIS milestone J (July 2004) will be the implementation of the ESMF compliant version of CLM in the LIS. As mentioned earlier, LIS also plans to use several Infrastructure utilities including regridding, I/O and communication services.

4.4 ALMA Interfaces in LIS

ALMA is a data exchange convention to facilitate the exchange of forcing data for LSM and the results produced by these schemes. The ALMA scheme enables inter-comparisons of land surface schemes and ensures that the implementation of proce-

dures to exchange data needs to be done only once. ALMA provides a list of variables needed to force LSMs and a summary of output variable definitions for LSM inter-comparisons.

By implementing the ALMA convention in the LIS driver, LIS can exchange data with other land surface modeling systems that are also ALMA compliant. Further, it will enable the use of LIS for intercomparison of land surface models for high resolution global modeling.

In order for LIS to be ALMA compliant, a number of interfaces need to be defined as shown in Figure 8. The forcing data is fetched from various locations on the internet, and after preprocessing is fed to the LIS driver, which in turns controls the execution of different LSMs. The input interface is expected to convert the forcing data into an ALMA compliant form. The ALMA wrappers for each LSM is expected to perform the translation of LIS driver variables to the LSM variables. The output interface is intended to convert the outputs from various LSMs into an ALMA format. Various design issues for these interfaces are discussed below.

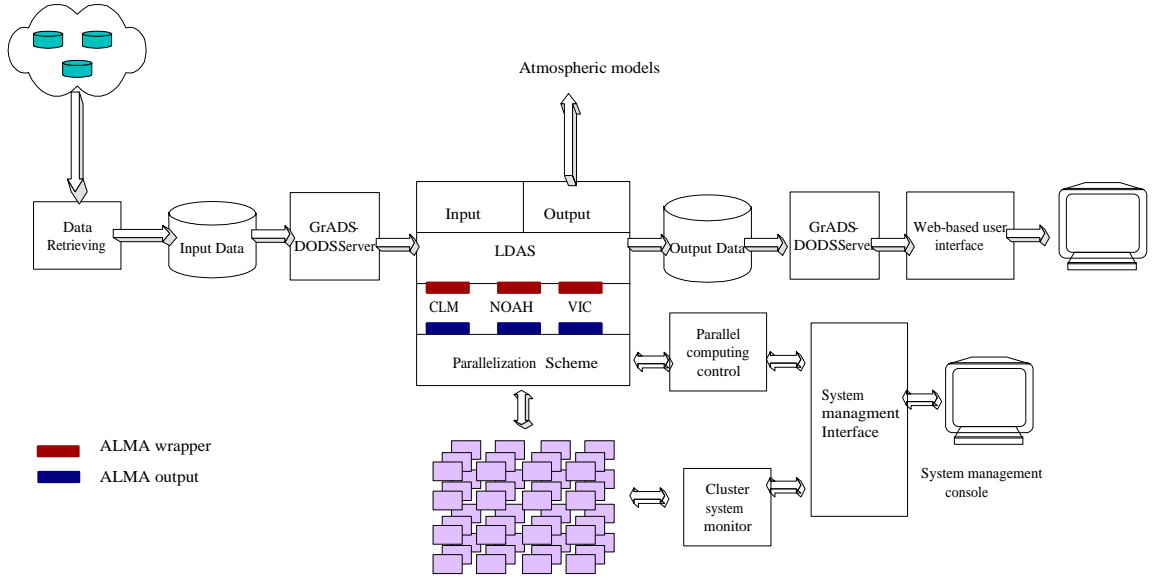


Figure 8: Proposed ALMA interfaces in LIS

4.4.1 Input Interface

Global atmospheric model predictions provide baseline forcing for LIS, but whenever possible, the modeled fields are replaced or corrected by observation-based fields. The global data are currently in various different data formats. The preprocessing

routines for input data will convert the fetched data from internet into a self describing data format such as netcdf/grib. The Input interface will make use of the metadata information present in these data files along with the input forcing ALMA definitions to generate an ALMA compliant format. Special attention need to be paid to the following issues.

- **Units :** All the required information to convert a forcing variable to the ALMA definition form need to be supplied. An exhaustive list of possibilities for the each forcing field need to be defined. Some special cases might also include dimensionless variables. For e.g, all the required information to convert a relative humidity value to a specific humidity value need to be specified.
- **Direction :** The sign conventions for each variable definition need to be converted to the ALMA format. Some forcing schemes might define a positive sign to be for an exchange from land to atmosphere, whereas another might consider positive sign to be for a downward direction from the sun to the earth. An exhaustive list of possible fields that need to convert a given directional definition to the ALMA format need to be specified.
- **Other issues:** The LIS driver might require some variables (derived or otherwise) that does not fall within the current definition of input ALMA definition. The input interface will provide these variables. Compliance to the ALMA input/output definitions is considered to be providing all the variables that are specified in the definition.

4.4.2 ALMA Wrappers

Each LSM scheme included in LIS is expected to be capable of receiving variables in the ALMA form. The ALMA wrappers for each LSM will perform the required conversion from LIS driver variables to LSM variables in accordance with the ALMA format. The design includes a list of conversions required. Tables 1, 2, and 3 shows the mapping of forcing data to the respective model variables for CLM, NOAH, and VIC, respectively.

4.4.3 Output Interface

Defining a generic output interface that converts output variables from different LSMs to an ALMA format is difficult, since explicit information is required to do the mapping from an LSM variable to a corresponding ALMA output variable. One of the intents of the ALMA standard is to put the onus of complying to the ALMA output standard on the LSMs so that intercomparisons between them can be done seamlessly.

Table 1: Mapping of Forcing variables to CLM input variables

| ALMA variable | Units | Sign | CLM variable | Units | Sign | Required Conversion |
|----------------|------------------------|------|-------------------|--------------------|------|---------------------|
| <i>Wind_N</i> | $\frac{m}{s}$ | N | <i>forc_u</i> | $\frac{m}{s}$ | N | - |
| <i>Wind_E</i> | $\frac{m}{s}$ | E | <i>forc_v</i> | $\frac{m}{s}$ | E | - |
| <i>Rainf</i> | $\frac{kg}{m^2 s}$ | D | <i>forc_rain</i> | $\frac{kg}{m^2 s}$ | D | - |
| <i>Snowf</i> | $\frac{kg}{m^2 s}$ | D | | | | |
| <i>Tair</i> | <i>K</i> | - | <i>forc_t</i> | <i>K</i> | - | - |
| <i>Qair</i> | $\frac{kg}{kg}$ | - | <i>forc_q</i> | - | - | - |
| <i>PSurf</i> | <i>Pa</i> | - | <i>forc_pbot</i> | <i>Pa</i> | - | - |
| <i>SWdown</i> | $\frac{W}{m^2}$ | D | <i>forc_solad</i> | $\frac{W}{m^2}$ | D | - |
| <i>LWdown</i> | $\frac{W}{m^2}$ | D | <i>forc_lwrad</i> | $\frac{W}{m^2}$ | D | - |
| <i>LSRainf</i> | $\frac{kg}{m^2 s}$ | - | | | | |
| <i>CRainf</i> | $\frac{kg}{m^2 s}$ | - | | | | |
| <i>CSnowf</i> | $\frac{kg}{m^2 s}$ | - | | | | |
| <i>LSSnowf</i> | $\frac{kg}{m^2 s}$ | - | | | | |
| <i>SVRainf</i> | $(\frac{kg}{m^2 s})^2$ | - | | | | |
| <i>SVSnowf</i> | $(\frac{kg}{m^2 s})^2$ | - | | | | |

Table 2: Mapping of Forcing variables to NOAH input variables

| ALMA variable | Units | Sign | NOAH variable | Units | Sign | Required Conversion |
|----------------|------------------------|------|----------------|-----------------|------|---------------------|
| <i>Wind_N</i> | $\frac{m}{s}$ | N | <i>VWIND</i> | $\frac{m}{s}$ | N | - |
| <i>Wind_E</i> | $\frac{m}{s}$ | E | <i>UWIND</i> | $\frac{m}{s}$ | E | - |
| <i>Rainf</i> | $\frac{kg}{m^2 s}$ | D | <i>PRCP</i> | $\frac{mm}{s}$ | D | - |
| <i>Snowf</i> | $\frac{kg}{m^2 s}$ | D | | | | |
| <i>Tair</i> | <i>K</i> | - | <i>SFCTEMP</i> | <i>K</i> | - | - |
| <i>Qair</i> | $\frac{kg}{kg}$ | - | <i>Q2</i> | - | - | - |
| <i>PSurf</i> | <i>Pa</i> | - | <i>SFCPRS</i> | <i>Pa</i> | - | - |
| <i>SWdown</i> | $\frac{W}{m^2}$ | D | <i>SOLDN</i> | $\frac{W}{m^2}$ | D | - |
| <i>LWdown</i> | $\frac{W}{m^2}$ | D | <i>LWDN</i> | $\frac{W}{m^2}$ | D | - |
| <i>LSRainf</i> | $\frac{kg}{m^2 s}$ | - | | | | |
| <i>CRainf</i> | $\frac{kg}{m^2 s}$ | - | <i>CPCP</i> | $\frac{mm}{s}$ | - | - |
| <i>CSnowf</i> | $\frac{kg}{m^2 s}$ | - | | | | |
| <i>LSSnowf</i> | $\frac{kg}{m^2 s}$ | - | | | | |
| <i>SVRainf</i> | $(\frac{kg}{m^2 s})^2$ | - | | | | |
| <i>SVSnowf</i> | $(\frac{kg}{m^2 s})^2$ | - | | | | |
| <i>Wind</i> | $\frac{m}{s}$ | - | <i>SFCSPD</i> | $\frac{m}{s}$ | - | - |

Table 3: Mapping of Forcing variables to VIC input variables

| ALMA variable | Units | Sign | VIC variable | Units | Sign | Required Conversion |
|----------------|------------------------|------|------------------|--------------------|------|---------------------|
| <i>Wind_N</i> | $\frac{m}{s}$ | N | <i>prec</i> | $\frac{kg}{m^2 s}$ | D | |
| <i>Wind_E</i> | $\frac{m}{s}$ | E | | | | |
| <i>Rainf</i> | $\frac{kg}{m^2 s}$ | D | | | | |
| <i>Snowf</i> | $\frac{kg}{m^2 s}$ | D | | | | |
| <i>Tair</i> | <i>K</i> | - | <i>air_temp</i> | <i>C</i> | | |
| <i>Qair</i> | $\frac{kg}{kg}$ | - | | - | - | - |
| <i>PSurf</i> | <i>Pa</i> | - | <i>pressure</i> | kPa | - | |
| <i>SWdown</i> | $\frac{W}{m^2}$ | D | <i>shortwave</i> | $\frac{W}{m^2}$ | D | - |
| <i>LWdown</i> | $\frac{W}{m^2}$ | D | <i>longwave</i> | $\frac{W}{m^2}$ | D | - |
| <i>LSRainf</i> | $\frac{kg}{m^2 s}$ | - | | | | |
| <i>CRainf</i> | $\frac{kg}{m^2 s}$ | - | | | - | |
| <i>CSnowf</i> | $\frac{kg}{m^2 s}$ | - | | | | |
| <i>LSSnowf</i> | $\frac{kg}{m^2 s}$ | - | | | | |
| <i>SVRainf</i> | $(\frac{kg}{m^2 s})^2$ | - | | | | |
| <i>SVSnowf</i> | $(\frac{kg}{m^2 s})^2$ | - | | | | |
| <i>Wind</i> | $\frac{m}{s}$ | - | <i>wind</i> | $\frac{m}{s}$ | - | - |

Table 4: Mapping of ALMA and CLM output variables : General Energy Balance

| ALMA variable | Units | Sign | Priority | CLM variable | Units | Sign | Status |
|--------------------|-----------------|--------|----------|--------------------------|-----------------|------|--------|
| <i>SWnet</i> | $\frac{W}{m^2}$ | D | M | <i>totfssa</i> | $\frac{W}{m^2}$ | D | Y |
| <i>LWnet</i> | $\frac{W}{m^2}$ | D | M | <i>toteflx_lwrad_net</i> | $\frac{W}{m^2}$ | D | Y |
| <i>Qle</i> | $\frac{W}{m^2}$ | U | M | <i>toteflx_lh_tot</i> | $\frac{W}{m^2}$ | U | Y |
| <i>Qh</i> | $\frac{W}{m^2}$ | U | M | <i>toteflx_sh_tot</i> | $\frac{W}{m^2}$ | U | Y |
| <i>Qg</i> | $\frac{W}{m^2}$ | D | M | <i>toteflx_soil_grnd</i> | $\frac{W}{m^2}$ | D | Y |
| <i>Qf</i> | $\frac{W}{m^2}$ | S to L | R | | | | U |
| <i>Qv</i> | $\frac{W}{m^2}$ | S to V | O | | | | U |
| <i>Qtau</i> | $\frac{N}{m^2}$ | D | R | | | | U |
| <i>Qa</i> | $\frac{W}{m^2}$ | D | O | | | | U |
| <i>DelSurfHeat</i> | $\frac{J}{m^2}$ | I | R | | | | U |
| <i>DelColdCont</i> | $\frac{J}{m^2}$ | I | R | | | | U |

LIS will adopt this philosophy, assuming that the LSMs are ALMA compliant. The sign column shows the direction of positive values (D (Downward), U (Upward), S to L (Solid to Liquid), S to V (Solid to Vapor), N (Northward), E (Eastward), Out (Out of grid cell) and In (Into grid cell))

ALMA output standard lists a number of mandatory variables that are required to do water and energy balance. The output interface will use these variables to compute water and energy balance calculations for different LSMs. The output of recommended and optional variables will depend on the LSM employed.

A mapping between lists of ALMA output variables and LSM variables are presented in Tables 4 to 27. Similar to the input interface, other LSMs in LIS are also expected to provide mapping between their output variables and ALMA output variables.

The ALMA standard categorizes each ALMA variables into a priority category, which appears in Tables 4 to 27 under the heading Priority. The priority indicates whether the variable is mandatory(M), recommended (R), or optional(O), to comply with the standard.

The status category in Tables 4 to 27 indicates the current status of the ALMA variable in the land surface model. A yes(Y) indicates that the ALMA mandatory variable is currently output from the model. A no(N) indicates that the ALMA mandatory variable does not exist in the current output from the model and would require changes in the model code to calculate the variable. An unavailable(U) variable indicates that the variable is not part of the model output currently.

Table 5: Mapping of ALMA and CLM output variables : General Water Balance

| ALMA variable | Units | Sign | Priority | CLM variable | Units | Sign | Status |
|---------------------|--------------------|--------|----------|------------------------|--------------------|--------|--------|
| <i>Snowf</i> | $\frac{kg}{m^2 s}$ | D | M | <i>totsnow</i> | $\frac{kg}{m^2 s}$ | D | Y |
| <i>Rainf</i> | $\frac{kg}{m^2 s}$ | D | M | <i>totrain</i> | $\frac{kg}{m^2 s}$ | D | Y |
| <i>Evap</i> | $\frac{kg}{m^2 s}$ | U | M | <i>totqflx_evap</i> | $\frac{kg}{m^2 s}$ | U | Y |
| <i>Qs</i> | $\frac{kg}{m^2 s}$ | Out | M | <i>totqflx_surf</i> | $\frac{kg}{m^2 s}$ | Out | Y |
| <i>Qrec</i> | $\frac{kg}{m^2 s}$ | In | O | | | | U |
| <i>Qsb</i> | $\frac{kg}{m^2 s}$ | Out | M | <i>totqflx_drain</i> | $\frac{kg}{m^2 s}$ | Out | Y |
| <i>Qsm</i> | $\frac{kg}{m^2 s}$ | S to L | M | <i>totqflx_snomelt</i> | $\frac{kg}{m^2 s}$ | S to L | U |
| <i>Qfz</i> | $\frac{kg}{m^2 s}$ | L to S | M | | | | U |
| <i>Qst</i> | $\frac{kg}{m^2 s}$ | - | R | | | | U |
| <i>DelSoilMoist</i> | $\frac{kg}{m^2}$ | I | M | | | | |
| <i>DelSWE</i> | $\frac{kg}{m^2}$ | I | M | <i>delswe</i> | $\frac{kg}{m^2}$ | I | Y |
| <i>DeslSurfStor</i> | $\frac{kg}{m^2}$ | I | M | | | | U |
| <i>DelIntercept</i> | $\frac{kg}{m^2}$ | I | R | | | | U |

Table 6: Mapping of ALMA and CLM output variables : Surface State Variables

| ALMA variable | Units | Sign | Priority | CLM variable | Units | Sign | Status |
|------------------|------------------|------|----------|-----------------|------------------|------|--------|
| <i>SnowT</i> | <i>K</i> | - | M | <i>snowtemp</i> | <i>K</i> | - | Y |
| <i>VegT</i> | <i>K</i> | - | M | <i>t_veg</i> | <i>K</i> | - | Y |
| <i>BareSoilT</i> | <i>K</i> | - | M | <i>t_grnd</i> | <i>K</i> | - | Y |
| <i>AvgSurfT</i> | <i>K</i> | - | M | <i>t_rad</i> | <i>K</i> | - | Y |
| <i>RadT</i> | <i>K</i> | - | M | <i>t_rad</i> | <i>K</i> | - | Y |
| <i>Albedo</i> | - | - | M | <i>surf alb</i> | - | - | Y |
| <i>SWE</i> | $\frac{kg}{m^2}$ | - | M | <i>h2ocan</i> | $\frac{kg}{m^2}$ | - | Y |
| <i>SWEVeg</i> | $\frac{kg}{m^2}$ | - | O | | | - | U |
| <i>SurfStor</i> | $\frac{kg}{m^2}$ | - | M | | | | N |

Table 7: Mapping of ALMA and CLM output variables : SubSurface State Variables

| ALMA variable | Units | Sign | Priority | CLM variable | Units | Sign | Status |
|-------------------|------------------|------|----------|----------------|-------|------|--------|
| <i>SoilMoist</i> | $\frac{kg}{m^2}$ | - | M | | - | - | Y |
| <i>SoilTemp</i> | <i>K</i> | - | R | | | | U |
| <i>SMLiqFrac</i> | - | - | O | | | | U |
| <i>SMFrozFrac</i> | - | - | O | | | | U |
| <i>SoilWet</i> | - | - | M | <i>soilwtc</i> | - | - | Y |

Table 8: Mapping of ALMA and CLM output variables : Evaporation Variables

| ALMA variable | Units | Sign | Priority | CLM variable | Units | Sign | Status |
|------------------|-------------------|------|----------|---------------|-------------------|------|--------|
| <i>PotEvap</i> | $\frac{kg}{m^2s}$ | U | R | | | | U |
| <i>ECanop</i> | $\frac{kg}{m^2s}$ | U | R | | | U | Y |
| <i>TVeg</i> | $\frac{kg}{m^2s}$ | U | M | <i>cantrn</i> | $\frac{kg}{m^2s}$ | U | Y |
| <i>ESoil</i> | $\frac{kg}{m^2s}$ | U | M | <i>bare</i> | $\frac{kg}{m^2s}$ | U | Y |
| <i>EWater</i> | $\frac{kg}{m^2s}$ | U | R | | | | U |
| <i>RootMoist</i> | $\frac{kg}{m^2}$ | - | M | <i>soilmr</i> | $\frac{kg}{m^2s}$ | | Y |
| <i>CanopInt</i> | $\frac{kg}{m^2}$ | - | R | | | - | Y |
| <i>EvapSnow</i> | $\frac{kg}{m^2}$ | - | R | | | - | Y |
| <i>SubSnow</i> | $\frac{kg}{m^2s}$ | - | R | | | - | Y |
| <i>SubSurf</i> | $\frac{kg}{m^2s}$ | - | R | | | | U |
| <i>ACond</i> | $\frac{m}{s}$ | - | M | <i>acond</i> | $\frac{m}{s}$ | - | Y |

Table 9: Mapping of ALMA and CLM output variables : Other hydrologic Variables

| ALMA variable | Units | Sign | Priority | CLM variable | Units | Sign | Status |
|--------------------|---------------|------|----------|--------------|-------|------|--------|
| <i>Dis</i> | $\frac{m}{s}$ | - | O | | | | U |
| <i>WaterTableD</i> | <i>m</i> | - | O | | | | N |

Table 10: Mapping of ALMA and CLM output variables : Cold Season Processes

| ALMA variable | Units | Sign | Priority | CLM variable | Units | Sign | Status |
|----------------------|-------|------|----------|--------------|-------|------|--------|
| <i>SnowFrac</i> | - | - | O | | | | U |
| <i>RainSnowFrac</i> | - | - | O | | | | U |
| <i>SnowfSnowFrac</i> | - | - | O | | | | U |
| <i>IceFrac</i> | - | - | O | | | | U |
| <i>IceT</i> | m | - | O | | | | U |
| <i>Fdepth</i> | m | - | O | | | | U |
| <i>Tdepth</i> | m | - | O | | | | U |
| <i>SAlbedo</i> | - | - | R | | | | U |
| <i>SnowTProf</i> | K | - | R | | | | U |
| <i>SnowDepth</i> | m | - | R | | | - | U |
| <i>SliqFrac</i> | - | - | R | | | | U |

Table 11: Mapping of ALMA and CLM output variables : Variables to be compared with remote sensed data

| ALMA variable | Units | Sign | Priority | CLM variable | Units | Sign | Status |
|---------------|-----------------|------|----------|--------------|-------|------|--------|
| <i>LWup</i> | $\frac{W}{m^2}$ | U | R | | | | |

Table 12: Mapping of ALMA and NOAH output variables : General Energy Balance

| ALMA variable | Units | Sign | Priority | NOAH variable | Units | Sign | Status |
|--------------------|-----------------|--------|----------|---------------|-----------------|------|--------|
| <i>SWnet</i> | $\frac{W}{m^2}$ | D | M | <i>soldn</i> | $\frac{W}{m^2}$ | D | Y |
| <i>LWnet</i> | $\frac{W}{m^2}$ | D | M | <i>lwdn</i> | $\frac{W}{m^2}$ | D | Y |
| <i>Qle</i> | $\frac{W}{m^2}$ | U | M | <i>eta</i> | $\frac{W}{m^2}$ | U | Y |
| <i>Qh</i> | $\frac{W}{m^2}$ | U | M | <i>shflx</i> | $\frac{W}{m^2}$ | U | Y |
| <i>Qg</i> | $\frac{W}{m^2}$ | D | M | <i>gflx</i> | $\frac{W}{m^2}$ | D | Y |
| <i>Qf</i> | $\frac{W}{m^2}$ | S to L | R | | | | U |
| <i>Qv</i> | $\frac{W}{m^2}$ | S to V | O | | | | U |
| <i>Qtau</i> | $\frac{W}{m^2}$ | D | R | | | | U |
| <i>Qa</i> | $\frac{W}{m^2}$ | D | O | | | | U |
| <i>DelSurfHeat</i> | $\frac{J}{m^2}$ | I | R | | | | U |
| <i>DelColdCont</i> | $\frac{J}{m^2}$ | I | R | | | | U |

Table 13: Mapping of ALMA and NOAH output variables : General Water Balance

| ALMA variable | Units | Sign | Priority | NOAH variable | Units | Sign | Status |
|---------------------|--------------------|--------|----------|--------------------------------------------------------------------------------|------------------|----------------------|--------|
| <i>Snowf</i> | $\frac{kg}{m^2 s}$ | D | M | <i>prcp</i> <i>evp</i> <i>runoff1</i> <i>runoff2</i> <i>snomlt</i> | $\frac{kg}{m^2}$ | D U Out Out | U |
| <i>Rainf</i> | $\frac{kg}{m^2 s}$ | D | M | | | | Y |
| <i>Evap</i> | $\frac{kg}{m^2 s}$ | U | M | | | | Y |
| <i>Qs</i> | $\frac{kg}{m^2 s}$ | Out | M | | | | Y |
| <i>Qrec</i> | $\frac{kg}{m^2 s}$ | In | O | | | | U |
| <i>Qsb</i> | $\frac{kg}{m^2 s}$ | Out | M | | | | Y |
| <i>Qsm</i> | $\frac{kg}{m^2 s}$ | S to L | M | | | | U |
| <i>Qfz</i> | $\frac{kg}{m^2 s}$ | L to S | M | | | | U |
| <i>Qst</i> | $\frac{kg}{m^2 s}$ | - | R | | | | U |
| <i>DelSoilMoist</i> | $\frac{kg}{m^2}$ | I | M | | | | |
| <i>DelSWE</i> | $\frac{kg}{m^2}$ | I | M | <i>delswe</i> | $\frac{kg}{m^2}$ | I | Y |
| <i>DeslSurfStor</i> | $\frac{kg}{m^2}$ | I | M | | | | U |
| <i>DelIntercept</i> | $\frac{kg}{m^2}$ | I | R | | | | U |

Table 14: Mapping of ALMA and NOAH output variables : Surface State Variables

| ALMA variable | Units | Sign | Priority | NOAH variable | Units | Sign | Status |
|------------------|------------------|------|----------|--------------------------------------------|------------------------------------------|--------------------------------------|--------|
| <i>SnowT</i> | <i>K</i> | - | M | <i>t1</i> <i>albedo</i> <i>sneqv</i> | <i>K</i> <i>-</i> $\frac{kg}{m^2}$ | - - - - - - - - | U |
| <i>VegT</i> | <i>K</i> | - | M | | | | U |
| <i>BareSoilT</i> | <i>K</i> | - | M | | | | Y |
| <i>AvgSurfT</i> | <i>K</i> | - | M | | | | Y |
| <i>RadT</i> | <i>K</i> | - | M | | | | Y |
| <i>Albedo</i> | - | - | M | | | | Y |
| <i>SWE</i> | $\frac{kg}{m^2}$ | - | M | | | | Y |
| <i>SWEVeg</i> | $\frac{kg}{m^2}$ | - | O | | | | U |
| <i>SurfStor</i> | $\frac{kg}{m^2}$ | - | M | | | | N |

Table 15: Mapping of ALMA and NOAH output variables : SubSurface State Variables

| ALMA variable | Units | Sign | Priority | NOAH variable | Units | Sign | Status |
|-------------------|------------------|------|----------|-----------------|------------------|------|--------|
| <i>SoilMoist</i> | $\frac{kg}{m^2}$ | - | M | <i>SMC</i> | $\frac{kg}{m^2}$ | - | Y |
| <i>SoilTemp</i> | <i>K</i> | - | R | | | | U |
| <i>SMLiqFrac</i> | - | - | O | | | | U |
| <i>SMFrozFrac</i> | - | - | O | | | | U |
| <i>SoilWet</i> | - | - | M | <i>mstautot</i> | - | - | Y |

Table 16: Mapping of ALMA and NOAH output variables : Evaporation Variables

| ALMA variable | Units | Sign | Priority | NOAH variable | Units | Sign | Status |
|------------------|-------------------|------|----------|---------------------------|-------------------|------|--------|
| <i>PotEvap</i> | $\frac{kg}{m^2s}$ | U | R | <i>ett</i> <i>edir</i> | $\frac{kg}{m^2s}$ | U | U |
| <i>ECanop</i> | $\frac{kg}{m^2s}$ | U | R | | | | Y |
| <i>TVeg</i> | $\frac{kg}{m^2s}$ | U | M | | | | Y |
| <i>ESoil</i> | $\frac{kg}{m^2s}$ | U | M | | | | Y |
| <i>EWater</i> | $\frac{kg}{m^2s}$ | U | R | <i>soilrz</i> | $\frac{kg}{m^2s}$ | - | U |
| <i>RootMoist</i> | $\frac{kg}{m^2}$ | - | M | | | | Y |
| <i>CanopInt</i> | $\frac{kg}{m^2}$ | - | R | | | | Y |
| <i>EvapSnow</i> | $\frac{kg}{m^2}$ | - | R | | | | Y |
| <i>SubSnow</i> | $\frac{kg}{m^2s}$ | - | R | | | | Y |
| <i>SubSurf</i> | $\frac{kg}{m^2s}$ | - | R | | | | U |
| <i>ACond</i> | $\frac{m}{s}$ | - | M | | | - | U |

Table 17: Mapping of ALMA and NOAH output variables : Other hydrologic Variables

| ALMA variable | Units | Sign | Priority | NOAH variable | Units | Sign | Status |
|--------------------|---------------|------|----------|---------------|-------|------|--------|
| <i>Dis</i> | $\frac{m}{s}$ | - | O | | | | U |
| <i>WaterTableD</i> | <i>m</i> | - | O | | | | N |

Table 18: Mapping of ALMA and NOAH output variables : Cold Season Processes

| ALMA variable | Units | Sign | Priority | NOAH variable | Units | Sign | Status |
|----------------------|-------|------|----------|---------------|-------|------|--------|
| <i>SnowFrac</i> | - | - | O | | | | U |
| <i>RainSnowFrac</i> | - | - | O | | | | U |
| <i>SnowfSnowFrac</i> | - | - | O | | | | U |
| <i>IceFrac</i> | - | - | O | | | | U |
| <i>IceT</i> | m | - | O | | | | U |
| <i>Fdepth</i> | m | - | O | | | | U |
| <i>Tdepth</i> | m | - | O | | | | U |
| <i>SAlbedo</i> | - | - | R | | | | U |
| <i>SnowTProf</i> | K | - | R | | | | U |
| <i>SnowDepth</i> | m | - | R | | | - | U |
| <i>SliqFrac</i> | - | - | R | | | | U |

Table 19: Mapping of ALMA and NOAH output variables : Variables to be compared with remote sensed data

| ALMA variable | Units | Sign | Priority | NOAH variable | Units | Sign | Status |
|---------------|-----------------|------|----------|---------------|-------|------|--------|
| <i>LWup</i> | $\frac{W}{m^2}$ | U | R | | | | |

Table 20: Mapping of ALMA and VIC output variables : General Energy Balance

| ALMA variable | Units | Sign | Priority | VIC variable | Units | Sign | Status |
|--------------------|-----------------|--------|----------|------------------|-----------------|----------|--------|
| <i>SWnet</i> | $\frac{W}{m^2}$ | D | M | <i>net_short</i> | $\frac{W}{m^2}$ | D | Y |
| <i>LWnet</i> | $\frac{W}{m^2}$ | D | M | | | | |
| <i>Qle</i> | $\frac{W}{m^2}$ | U | M | <i>latent</i> | $\frac{W}{m^2}$ | U | Y |
| <i>Qh</i> | $\frac{W}{m^2}$ | U | M | <i>sensible</i> | $\frac{W}{m^2}$ | U | Y |
| <i>Qg</i> | $\frac{W}{m^2}$ | D | M | <i>grnd_flux</i> | $\frac{W}{m^2}$ | D | Y |
| <i>Qf</i> | $\frac{W}{m^2}$ | S to L | R | | | | U |
| <i>Qv</i> | $\frac{W}{m^2}$ | S to V | O | | | | |
| <i>Qtau</i> | $\frac{N}{m^2}$ | D | R | | | | U |
| <i>Qa</i> | $\frac{W}{m^2}$ | D | O | <i>advection</i> | $\frac{W}{m^2}$ | D | Y |
| <i>DelSurfHeat</i> | $\frac{J}{m^2}$ | I | R | | | | U |
| <i>DelColdCont</i> | $\frac{J}{m^2}$ | I | R | <i>deltaCC</i> | $\frac{J}{m^2}$ | Increase | Y |

5 Final Remarks

The goal of LIS is to develop a leading edge land surface modeling and data assimilation system to support broad land surface research and application activities, to help define earth system modeling interoperability standards, and to lead the effective application of high performance computing to high-resolution, real-time earth system studies. The framework oriented design of LIS presented in this document and the use and adoption of standards such as ESMF and ALMA helps in providing a platform for land surface modelers and researchers. The extensible interfaces in LIS helps to ease the cost of development of new applications. Utilities such as tools for high performance computing and data assimilation helps researchers in rapid prototyping and development. Further, participation in the standards laid out by ESMF also helps in coupling with other earth system models.

References

- [1] ALMA. <http://www.lmd.jussieu.fr/ALMA>.
- [2] CLM. <http://www.cgd.ucar.edu/tss/clm/>.
- [3] ESMF. <http://www.esmf.ucar.edu>.
- [4] GLDAS. <http://ldas.gsfc.nasa.gov>.

Table 21: Mapping of ALMA and VIC output variables : General Water Balance

| ALMA variable | Units | Sign | Priority | VIC variable | Units | Sign | Status |
|---------------------|-------------------|--------|----------|-----------------|-----------------|------|--------|
| <i>Snowf</i> | $\frac{kg}{m^2s}$ | D | M | | | | U |
| <i>Rainf</i> | $\frac{kg}{m^2s}$ | D | M | <i>prec</i> | $\frac{mm}{hr}$ | D | Y |
| <i>Evap</i> | $\frac{kg}{m^2s}$ | U | M | <i>evap</i> | $\frac{mm}{hr}$ | U | Y |
| <i>Qs</i> | $\frac{kg}{m^2s}$ | Out | M | <i>runoff</i> | $\frac{mm}{hr}$ | Out | Y |
| <i>Qrec</i> | $\frac{kg}{m^2s}$ | In | O | | | | N |
| <i>Qsb</i> | $\frac{kg}{m^2s}$ | Out | M | <i>baseflow</i> | $\frac{mm}{hr}$ | Out | Y |
| <i>Qsm</i> | $\frac{kg}{m^2s}$ | S to L | M | | | | U |
| <i>Qfz</i> | $\frac{kg}{m^2s}$ | L to S | M | | | | U |
| <i>Qst</i> | $\frac{kg}{m^2s}$ | - | R | | | | U |
| <i>DelSoilMoist</i> | $\frac{kg}{m^2}$ | I | M | | | | |
| <i>DelSWE</i> | $\frac{kg}{m^2}$ | I | M | | | | |
| <i>DeslSurfStor</i> | $\frac{kg}{m^2}$ | I | M | | | | U |
| <i>DelIntercept</i> | $\frac{kg}{m^2}$ | I | R | | | | U |

Table 22: Mapping of ALMA and VIC output variables : Surface State Variables

| ALMA variable | Units | Sign | Priority | VIC variable | Units | Sign | Status |
|------------------|------------------|------|----------|--------------------|-----------|------|--------|
| <i>SnowT</i> | <i>K</i> | - | M | | | | U |
| <i>VegT</i> | <i>K</i> | - | M | | | | U |
| <i>BareSoilT</i> | <i>K</i> | - | M | | | | U |
| <i>AvgSurfT</i> | <i>K</i> | - | M | <i>surf_temp</i> | <i>C</i> | - | Y |
| <i>RadT</i> | <i>K</i> | - | M | <i>rad_temp</i> | <i>K</i> | - | Y |
| <i>Albedo</i> | - | - | M | <i>albedo</i> | - | - | Y |
| <i>SWE</i> | $\frac{kg}{m^2}$ | - | M | <i>swq</i> | <i>mm</i> | - | Y |
| <i>SWEVeg</i> | $\frac{kg}{m^2}$ | - | O | <i>snow_canopy</i> | <i>mm</i> | - | Y |
| <i>SurfStor</i> | $\frac{kg}{m^2}$ | - | M | | | | |

Table 23: Mapping of ALMA and VIC output variables : SubSurface State Variables

| ALMA variable | Units | Sign | Priority | VIC variable | Units | Sign | Status |
|-------------------|------------------|------|----------|--------------|-----------|------|--------|
| <i>SoilMoist</i> | $\frac{kg}{m^2}$ | - | M | <i>moist</i> | <i>mm</i> | - | Y |
| <i>SoilTemp</i> | <i>K</i> | - | R | | | | U |
| <i>SMLiqFrac</i> | - | - | O | | | | U |
| <i>SMFrozFrac</i> | - | - | O | | | | U |
| <i>SoilWet</i> | - | - | M | | | | U |

Table 24: Mapping of ALMA and VIC output variables : Evaporation Variables

| ALMA variable | Units | Sign | Priority | VIC variable | Units | Sign | Status |
|------------------|-------------------|------|----------|-------------------|-----------------|------|--------|
| <i>PotEvap</i> | $\frac{kg}{m^2s}$ | U | R | | | | U |
| <i>ECanop</i> | $\frac{kg}{m^2s}$ | U | R | <i>evap_canop</i> | $\frac{mm}{hr}$ | U | Y |
| <i>TVeg</i> | $\frac{kg}{m^2s}$ | U | M | <i>evap_veg</i> | $\frac{mm}{hr}$ | U | Y |
| <i>ESoil</i> | $\frac{kg}{m^2s}$ | U | M | <i>evap_bare</i> | $\frac{mm}{hr}$ | U | Y |
| <i>EWater</i> | $\frac{kg}{m^2s}$ | U | R | | | | U |
| <i>RootMoist</i> | $\frac{kg}{m^2}$ | - | M | | | | N |
| <i>CanopInt</i> | $\frac{kg}{m^2}$ | - | R | <i>Wdew</i> | $\frac{mm}{hr}$ | - | Y |
| <i>EvapSnow</i> | $\frac{kg}{m^2}$ | - | R | <i>sub_snow</i> | $\frac{mm}{hr}$ | - | Y |
| <i>SubSnow</i> | $\frac{kg}{m^2s}$ | - | R | <i>sub_canop</i> | $\frac{mm}{hr}$ | - | Y |
| <i>SubSurf</i> | $\frac{kg}{m^2s}$ | - | R | | | | U |
| <i>ACond</i> | $\frac{m}{s}$ | - | M | | | | U |

Table 25: Mapping of ALMA and VIC output variables : Other hydrologic Variables

| ALMA variable | Units | Sign | Priority | VIC variable | Units | Sign | Status |
|--------------------|---------------|------|----------|--------------|-------|------|--------|
| <i>Dis</i> | $\frac{m}{s}$ | - | O | | | | U |
| <i>WaterTableD</i> | <i>m</i> | - | O | | | | N |

Table 26: Mapping of ALMA and VIC output variables : Cold Season Processes

| ALMA variable | Units | Sign | Priority | VIC variable | Units | Sign | Status |
|----------------------|-------|------|----------|-------------------|-----------|------|--------|
| <i>SnowFrac</i> | - | - | O | <i>snow_depth</i> | <i>cm</i> | - | U |
| <i>RainSnowFrac</i> | - | - | O | | | | U |
| <i>SnowfSnowFrac</i> | - | - | O | | | | U |
| <i>IceFrac</i> | - | - | O | | | | U |
| <i>IceT</i> | m | - | O | | | | U |
| <i>Fdepth</i> | m | - | O | | | | U |
| <i>Tdepth</i> | m | - | O | | | | U |
| <i>SAlbedo</i> | - | - | R | | | | U |
| <i>SnowTProf</i> | K | - | R | | | | U |
| <i>SnowDepth</i> | m | - | R | | | | Y |
| <i>SliqFrac</i> | - | - | R | | | | U |

Table 27: Mapping of ALMA and VIC output variables : Variables to be compared with remote sensed data

| ALMA variable | Units | Sign | Priority | VIC variable | Units | Sign | Status |
|---------------|-----------------|------|----------|--------------|-------|------|--------|
| <i>LWup</i> | $\frac{W}{m^2}$ | U | R | | | | |

- [5] LIS. <http://lis.gsfc.nasa.gov>.
- [6] NOAH. <ftp://ftp.ncep.noaa.gov/pub/gcp/ldas/noahls/>.
- [7] VIC. <http://hydrology.princeton.edu/research/lis/index.html>.